HIGH ALTITUDE OBSERVATORY
of
Harvard University and University of Colorado

TECHNICAL REPORT

to the

OFFICE OF NAVAL RESEARCH

Photometric Standardization of Eclipse Spectra

by

Donald E. Billings*
Eugene N. Parker**

15 July 1952

ONR Contract Nonr-393 (01)
Project NRL Req. 173/5671/51

*High Altitude Observatory of Harvard University and University of Colorado, Boulder, Colorado.
**University of Utah, Salt Lake City, Utah.

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OUTLINE

FOREWARD
(By Walter Orr Roberts)

Before we carried out the expedition to the eclipse of 25 February 1952 in the Sudan, we carefully worked out plans for photometric standardization of the films. This report, though it is being issued after the completion of the expedition, was prepared beforehand. The report is a composite of contributions by the two authors. Schedule difficulties were so severe, however, that we deferred the editing and issuing of the report until after the more essential tasks were done. We shall soon be able to commence the reduction of the spectra according to the general procedures related here. The results of our expedition have already been related in a report and proposal prepared under research contract.*

PHOTOMETRIC STANDARDIZATION OF ECLIPSE SPECTRA

I. General Procedure.

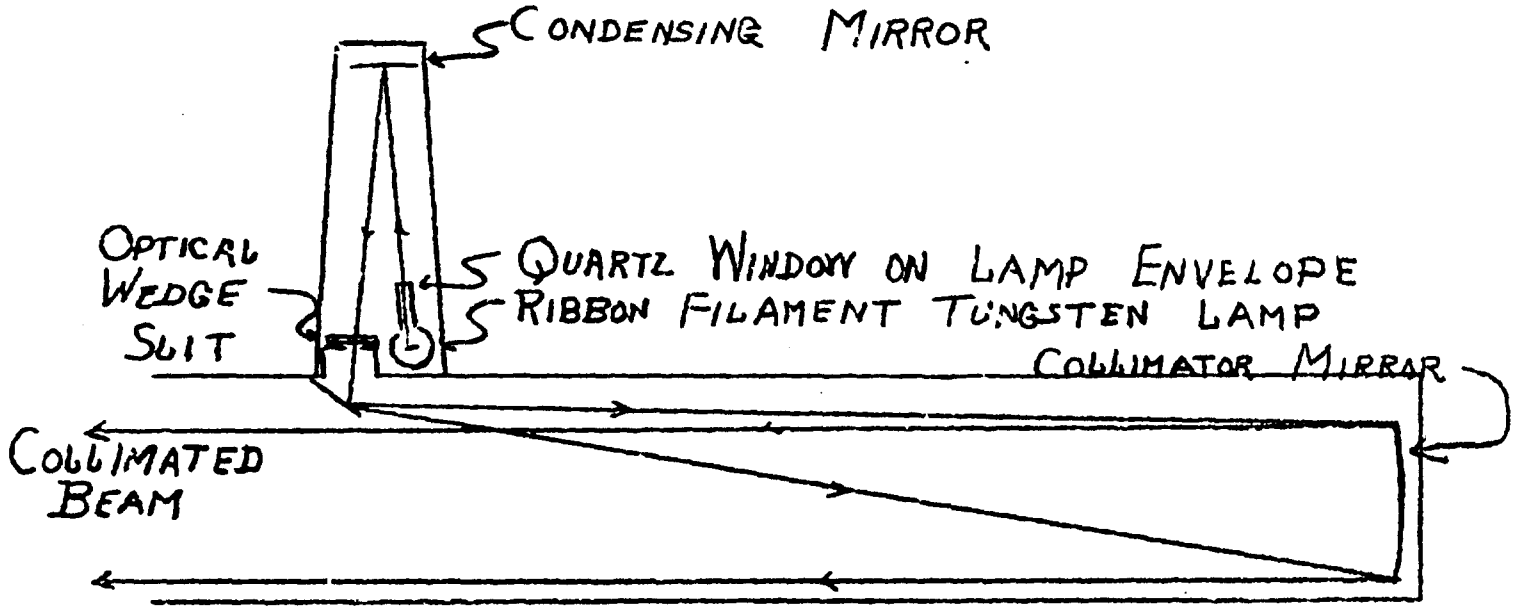
Our purpose is to determine the energy of each wavelength which enters the aperture of the eclipse camera from any specified sectional area of the chromosphere during the eclipse. To determine this from the photographic plates requires a knowledge of the energy $E(\lambda, P, D)$ of wavelength λ incident on the camera aperture during an exposure of time duration P which will blacken one square centimeter of the plate to a density D. Hence, if dA represents an area of the solar disk located in the exposed portion of the chromosphere, and da is the image of dA in wavelength λ falling on the photographic plate, E da is the energy of wavelength λ entering the camera from dA.

$E(\lambda, P, D)$ is determined by comparison of the eclipse spectrum with a standardizing spectrum. The standardizing spectrum, obtained with the same eclipse camera and upon the same film as the eclipse as the eclipse spectrum, is that of light from a collimator. The slit of the collimator is illuminated by a standard tungsten ribbon-filament lamp with a quartz window, and over the slit is a metal-on-quartz wedge the density of which varies continuously from 0.2 to 2.2. An image of unit magnification of the ribbon filament is thrown upon the slit by a four-inch condensing mirror, and the slit is made as wide as is possible under the restriction that it be completely illuminated by the filament image. The collimator lens is an eight-inch parabolic mirror

*Walter Orr Roberts, Supplementary Proposal to the Naval Research Laboratory for Contract Extension, 21 March 1952, 12 pages.

FIGURE 1

(Sketch of Optical System of the Collimator)



Because of the wedge in front of the collimator slit, the standardizing spectrum is graded in density, at each wavelength, along a direction normal to the direction of dispersion. $E(\lambda, P, D)$ corresponding to a given point on a line in the eclipse spectrum may be obtained from a determination of the point at the same wavelength in the standardizing spectrum which has the same photographic density, provided:

(a) The photography of the eclipse and of the standardizing spectra may be considered identical.

(b) The standardizing film has been calibrated so that for each point (x measured along the collimator slit, λ) there is assigned a value $E(\lambda, P, x)$ for the energy of wavelength λ from the collimator which produces upon unit area of the film in time P the degree of blackening found at point (λ, x). Since point (λ, x) is chosen because it has the same blackening as the point of interest at wavelength λ in the eclipse spectrum:

(1) $E(\lambda, P, D) = E(\lambda, P, x)$

(Note that the coordinate x is measured along the collimator slit. In what follows the same coordinate x will be assigned to any point in any spectrum from the collimator that is the image of the point in the slit units from the end of the slit.)

II. Method of Identifying Eclipse and Standardizing Spectra Photography.

Each eclipse and standardizing spectrum has, in a 5 mm. strip directly under the spectrum, a photograph of the data panel. The data panel has two parts:

(1) A timing device consisting of a watt-hour meter driven by a synchronous motor at such a rate that the fastest moving hand turns once each second. On each hand of the meter is mounted a stainless-steel sphere in which is formed the image of a point source of light. Each image photographs as an arc, the length of exposure and time at which the exposure was made being determined by the lengths and positions of these arcs.

(2) A step-wedge, densitites 0.3 to 3.8, illuminated by a ribbon-filament lamp the current through which is carefully controlled.

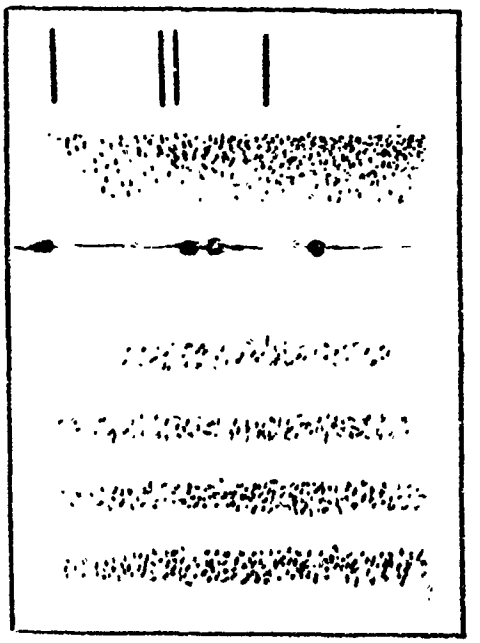
A standardizing spectrum is considered to be photographically equivalent to an eclipse spectrum if the photographic characteristic curves plotted for the two from the step-wedge densities are identical. It is desirable that the exposure times also be nearly equal, but it is not essential that they be exactly equal. In other words, small differences in emulsion or development may be cancelled by differences in exposure time; large differences cannot be so cancelled. The need for matching photographic characteristics requires the photographing of a large number of standardizing spectra, with the exposure time and developmental features varying over the same range as they do in the eclipse spectra photographs.

III. Method of Calibrating the Standardizing Spectra.

A. Procedure.

The standardizing spectra are calibrated by comparison of spectra taken from the collimator with spectra taken directly from the ribbon filament of the lamp. This comparison is carried out in the field using the eclipse cameras themselves, and in the laboratory using a special spectrograph designed for the purpose. In either case, a spectrum from the collimator, called the calibrating spectrum, is first photographed. The standard lamp is then removed from the collimator and placed at a considerable distance from the spectrograph. The spectrograph is directed away from the collimator and toward the standard lamp, and a series of spectra of the standard lamp filament are photographed, using a graded series of spectrograph apertures. The appearance of the resulting calibrating film is as follows:

FIGURE 2



In addition to the continuous spectra, two bright-line spectra are photographed on each film — one using the bright-line source to illuminate the collimator slit, the other with the bright-line source located at the same position as is the ribbon filament when photographed directly. The bright-line spectra are used both to identify the wavelengths and to give the dispersion in the continuous spectra. $E(\lambda, P, x)$ is determined from a comparison of the filament spectra with the collimator spectrum to find which of the filament spectra has, at wavelength λ, the same density as the density in the collimator spectrum at the point (λ, x).

B. Theory.

The standard ribbon-filament lamp has been calibrated by the Bureau of Standards Pyrometry Laboratory, giving the brightness temperature (1948 scale) as a function of lamp current. The filament current is held at a constant value by means of a saturated core reactor type of stabilizing circuit, this value being determined to four significant figures by potentiometric measurement of the potential drop across a standard resistor in series with the lamp. Knowing this temperature, we determine the brightness temperature of the lamp from its calibration, and the true temperature is computed by the relationship:

$$(2)\quad 1/T - 1/S = \frac{2.303 \log \epsilon}{c_2}$$

where c_2 is Planck's second coefficient, and ϵ is the emissivity of tungsten.

In order to proceed further, it is necessary to know the emissivity of tungsten as a function of filament temperature and wavelength. Emissivities of tungsten as a function of wavelength, as published by various observers, are plotted at various temperatures in Figure 3. It is noted that in the range 4500 A to 7500 A these results agree to within approximately 1%. Within this region of agreement the data are contained by a system of parallel stright lines. The data of Forsythe and Adams approximates the straight-line relationships beyond this range, differing only in that the curves for the various temperatures draw closer together for shorter and longer wavelengths. The results of the other two observers, however, introduce discrepencies of the order of 12%, both at 3200 A and 9000 A.

To analyze these emissivity data for our own use, the following approach is suggested: It is noted that the data of Forsythe and Adams for wavelengths greater than 6500 A define a rather clear-cut series of straight lines which converge for longer wavelengths. Measurements carried further into the infrared region show that the lines continue to converge and eventually intersect. Hence their extrapolation into the long wavelength range has experimental justification. If they are extrapolated into the short wavelength range they will contain the data both of Forsythe and Adams and of Ornstein, and will approximate the data of Hoffman and Willenberg more closely than does that of Forsythe and Adams. It is suggested, therefore, that the emissivity of tungsten as a function of wavelength at a given temperature be taken as the straight line which at that temperature fits the data of Forsythe and Adams for the wavelength range from 6500 A to 10,000 A.

Given the emissivity, the true temperature, and the area of the filament, the energy radiated from it per second per unit wavelength per unit solid angle

$$(3) \quad \frac{\partial^2 U}{\partial \Omega \, \partial \lambda} = \epsilon J_\lambda$$

where ϵ is the emissivity and J_λ is computed by the Planck Radiation Law.

Let A be the area of the aperture of the calibrating spectrograph when the calibrating spectrum is obtained, and a the area when that direct-filament spectrum is obtained which has the same density at wavelength λ as that at (λ, x) in the calibrating spectrum.

Let:

D be the dispersion in the collimator calibrating spectrum, cm./A

d be the dispersion in the direct-filament spectrum, cm./A

M be the linear magnification in the collimator spectrum

m be the linear magnification in the direct-filament spectrum

h be the height of the filament

R be the distance from the filament to the aperture of the spectrograph.

Then for a direct-filament exposure of exposure-time P, the energy direct from the filament within the interval $d\lambda$ entering the spectrograph is:

(4) entering energy $= P\, a/R^2\, \epsilon\, J_\lambda\, d\lambda$

This energy will fall upon a strip hm centimeters high and $d\, d\lambda$ cm. long. Hence the energy falling per unit area upon the photographic film is:

$$(5)\quad \frac{1}{hm\ d\ d\lambda} \cdot P\,\frac{a}{R^2}\ \epsilon\ J_\lambda\ d\lambda \equiv \frac{Pa\,\epsilon\,J_\lambda}{hmR^2d}$$

Let $W(\lambda, P, x)d\lambda\ dx$ be the energy per square centimeter in the light from the collimator tube in the range $d\lambda$ and emitted from a length dx of the slit. The energy entering the spectrograph is then $AW\ d\lambda\ dx$. This energy falls upon an area Mdx long and $Dd\lambda$ wide. Hence the energy per unit area falling on the photographic plate is:

$$(6)\quad \frac{AW\ dx\ d\lambda}{MD\ dx\ d\lambda} \equiv \frac{AW}{MD}$$

If the blackening of the photographic plate is the same at the point (λ, x) as for the direct-filament exposure discussed above:

$$(7)\quad \frac{AW}{MD} = \frac{Pa\,\epsilon\,J_\lambda}{hm\,R^2d}$$

$$(8)\quad W = \frac{1}{A}\,\frac{M}{m}\,\frac{D}{d}\,\frac{P\,\epsilon\,J_\lambda}{hR^2}$$

Finally, in the photography of the standardizing spectrum, let A' be the aperture of the eclipse camera, M' be the magnification in photographing the collimator spectrum, and D' the dispersion.

The energy of wavelength $d\lambda$ from length dx of slit, $A'W dx d\lambda$, enters the eclipse camera and is distributed over an area M'dx high and D'dλ wide. Hence:

$$(9)\quad E(\lambda,P,x) = \frac{A'W\,dx\,d\lambda}{M'D'dx\,d\lambda} \equiv \frac{A'W}{M'D'}$$

Substituting for W from (7)

$$(10)\quad E(\lambda,P,x) = \frac{aA'}{A}\ \frac{M}{M'm}\ \frac{D}{D'd}\ \frac{P\epsilon J\lambda}{hR^2}$$

Or, substituting from the Planck Radiation Law:

$$(11)\quad E(\lambda,P,x) = \frac{aA'}{A}\ \frac{M}{M'm}\ \frac{D}{D'd}\ \frac{Pbc_1}{R^2}\ \frac{\lambda^{-5}\epsilon}{\epsilon^{c_2/\lambda T}-1}$$

where b is the width of the filament.

C. Limitations of the Method.

In principle $E(\lambda,P,x)$ for all points (λ,x) in the standardizing spectrum may be determined by the above method. There are two limitations, however.

(1) Because of local irregularities in any photographic plate, any satisfactory calibration must be based on a number of independent photographs. The process followed — setting up a spectrograph on the collimator, photographing a bright-line source, removing the bright-line source, illuminating the slit with a standard lamp, photographing a calibrating spectrum removing the standard lamp from the collimator and placing it at a distant point, readjusting the spectrograph to photograph the lamp in its new position, taking several photographs through different apertures, removing the standard lamp and replacing it with a bright-line source, and photographing the bright-line source — is time consuming to the extent that the taking of a large number of data for averaging is prohibitive.

(2) In those portions of the calibrating spectrum which are exposed to very low and very high densities it is difficult to locate critically the point which has the same density as a corresponding point in a direct-filament spectrum.

D. Modifications of the Method.

Because of the limitations listed in part III, the method outlined above is used only for accurate determination of $E(\lambda, P, x)$ for a band of points (extending over all wavelengths in the calibrating spectrum) in which the densities are those in the steep part of the photographic characteristic curve. Data for evaluating $E(\lambda, P, x)$ for other points are obtained by two methods:

(1) After a calibrating spectrum is photographed through an aperture A_1, the aperture of the camera is changed and other spectra from the collimator are photographed on the same photographic plate through apertures A_2, A_3, etc. If $E(\lambda, P, x_1)$ has been determined at point (λ, x_1) by the general method outlined in sections C-I and C-II, and the density at point (λ, x_2) in the photograph taken through aperture A_2 is the same as that at (λ, x_1) in the photograph taken through aperture A_1, then:

$$(12)\quad E(\lambda, P, x_2) = \frac{A_1}{A_2} E(\lambda, P, x_1)$$

(2) After the calibrating spectrum is photographed with the filament at temperature T_1, the temperature is altered and other spectra from the collimator are photographed on the same photographic plate with the filament at temperatures T_2, T_3, etc. If $E(\lambda, P, x_1)$ has been determined at point (λ, x_1) by the general method outlined in sections C-I and C-II, and the density at point (λ, x_2) in the photograph taken with the filament at temperature T_2 is the same as that at point (λ, x_1) in the photograph taken with the filament temperature at temperature T_1, then:

$$(13)\quad E(\lambda, P, x_2) = \frac{J_{\lambda, T_1}}{, T_2} E(\lambda, P, x_1)$$

The filament temperature and the spectrograph aperture are equally easy to vary. By varying either, many times as many data are accumulated in a given working time as can be accumulated in the same time by the general method. Furthermore, it is possible to determine the calibration of all points by the use of photographic densities which are critically dependent upon position in the spectra.

The computations in the temperature-variation method are somewhat more involved than those in the aperture-variation method. When the two are used jointly, however, a check of the temperature calibration of the filament is achieved in addition to the calibration of the standardizing spectrum.

E. Calibration Results.

If the transmission of the collimator, including the wedge, is

not a function of wavelength, the points in a calibrating spectrum which have the same density as points of corresponding wavelength in a given direct-filament spectrum should all have the same value of x. Whether or not the transmission is independent of the wavelength, the locus of points in the calibrating spectrum which have the same density as points of corresponding wavelength in a given direct-filament spectrum constitutes a contour of equal transmissivity for the wedge-collimator system.

Figure 4 represents a system of such contours in the ultraviolet region. The number assigned to a contour is the logarithm of the ratio of the aperture used in the direct-filament shot from which the contour was drawn to the smallest aperture used for direct-filament shots. Contours from 0.00 to 1.00 were obtained by the general method (C-I and C-II); others were obtained by the method C-IV(b). Each point represents the average of three data.

Along any contour the coefficient in brackets in equation (11) is a constant. The function of wavelength lying outside the brackets is independent of the contour. Hence, once a set of contours is established over the entire range of (λ, x), $E(\lambda, P, x)$ can be immediately determined as a product of two easily computed functions.

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Technical Report

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FIGURE 3

Emissivities of Tungsten

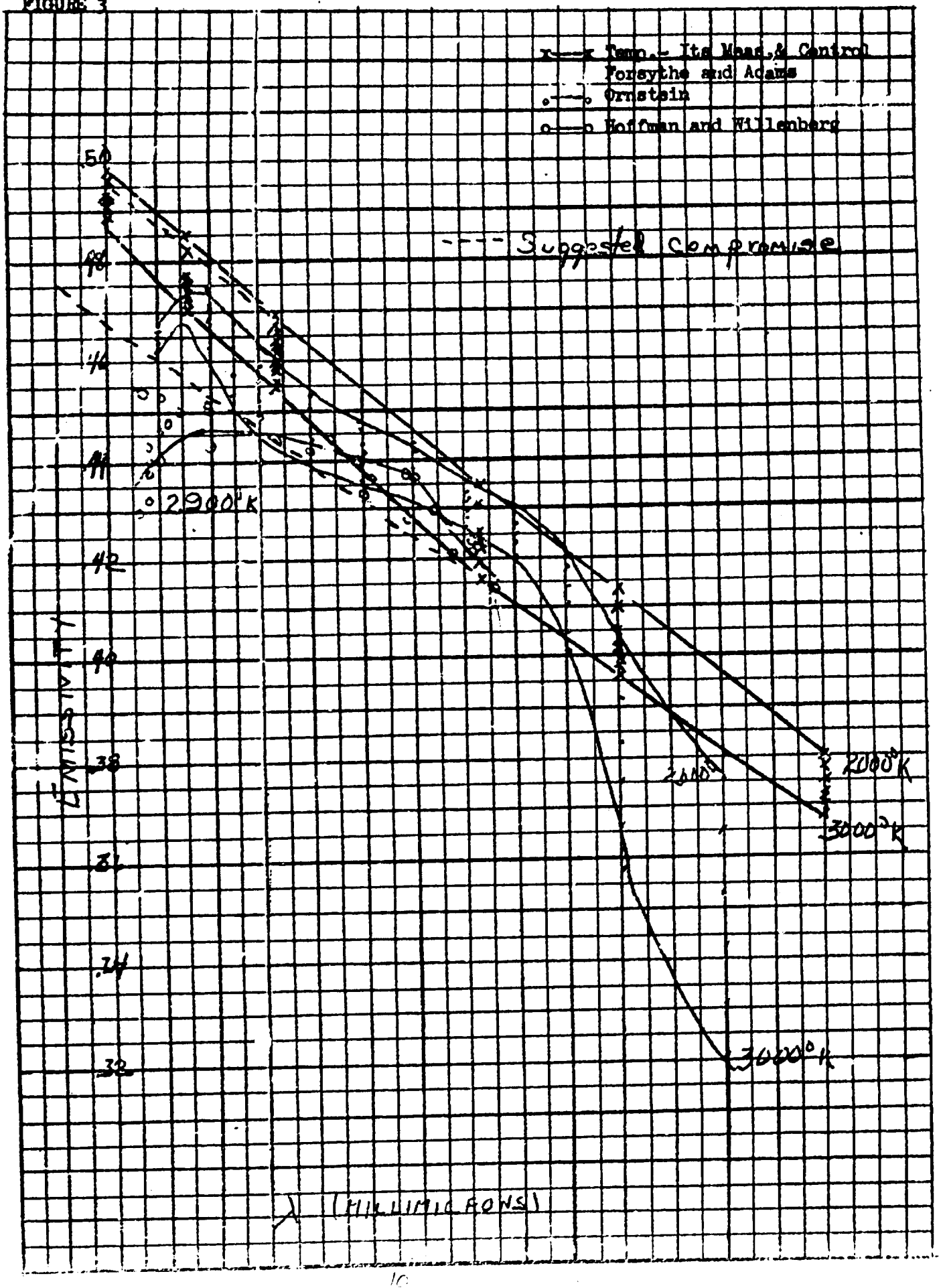

FIGURE 4

Collimator Contours of Equal Transmission

21 November 1951 From SUV